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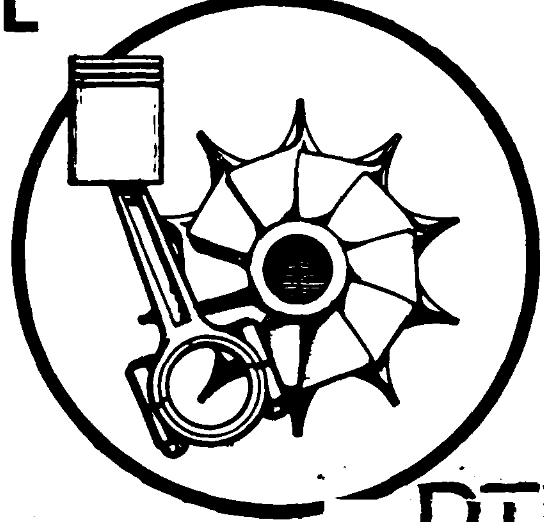
NASA CR-175110

COMPOUND CYCLE ENGINE FOR HELICOPTER APPLICATION



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16. Abstract

The Compound Cycle Engine (CCE) is a highly turbocharged, power compounded, ultra-high power density, light-weight diesel engine. The turbomachinery is similar to a moderate pressure ratio, free power turbine gas turbine engine and the diesel core is high speed and a low compression ratio. This engine is considered a potential candidate for future military light helicopter applications.

This executive summary presents cycle thermodynamic (SFC) and engine weight analyses performed to establish general engine operating parameters and configuration. An extensive performance and weight analysis based on a typical two hour helicopter (+30 minute reserve) mission determined final conceptual engine design. With this mission, CCE performance was compared to that of a T-800 class gas turbine engine. The CCE had a 31% lower-fuel consumption and resulted in a 16% reduction in engine plus fuel and fuel tank weight. Design SFC of the CCE is 0.33 lb/HP-HR and installed wet weight is 0.43 lbs/HP.

The major technology development areas required for the CCE are identified and briefly discussed.

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COMPOUND CYCLE ENGINE FOR HELICOPTER APPLICATION

INTRODUCTION

This report is provided as an executive summary of a study funded by the U.S. Army Aviation Systems Command on the subject of compound cycle engines for helicopter applications. This effort, conducted jointly with NASA and under contract with the Garrett Turbine Engine Company (GTEC), has been underway since mid-1984 (Reference: Contract NAS3-24346).

A Compound Cycle Engine (CCE) as shown in Figure 1 combines the airflow capacity and light-weight features of a gas turbine with the highly efficient but heavier diesel. The compressor of the gas turbine module delivers high pressure air to the diesel core where further compression takes place in the cylinders (as with a conventional reciprocating compressor). Fuel is introduced and burned at very high pressure and temperature, and power is extracted in the downstroke of the diesel piston. The discharge gas, with its remaining energy, then is ducted to turbines that drive the compressor and also augment the output of the diesel core. The term compound cycle, therefore, is an expression used to describe the process in which excess power is extracted from the turbomachinery and compounded through gearing to add to the output of the diesel core.

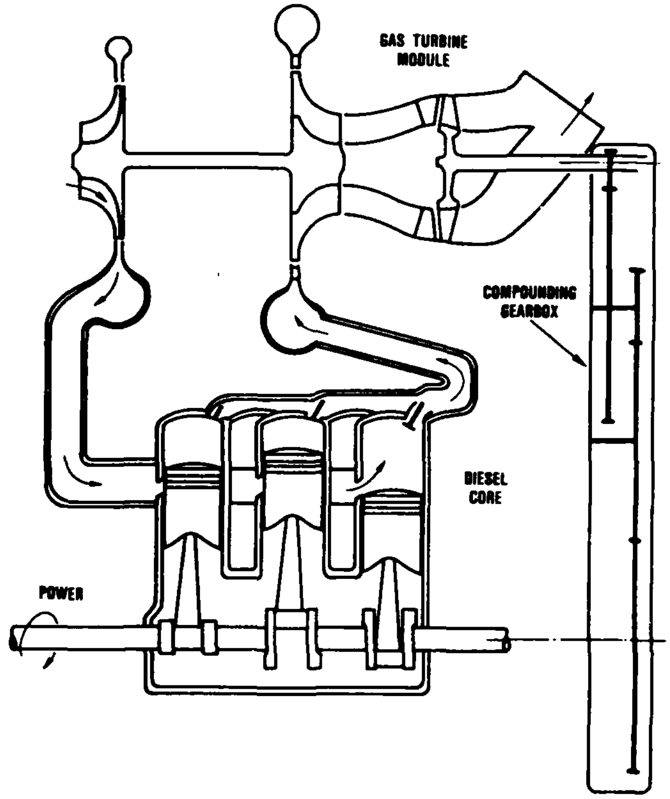


Figure 1. Arrangement of Compound Cycle Engine.

Recent studies by the Army have revealed that fuel constitutes 70 percent of the tonnage required to supply and support its forces under battlefield conditions. Other preliminary studies by AVSCOM supported by Compound Cycle Turbofan Engine (CCTE) information obtained under DARPA/U.S. Air Force Contract F33657-77-C-0391, indicated that a 40 percent fuel savings potential exists for compound cycle engine powered helicopters. A 23 percent reduction in required engine power (installed) was also estimated for the same mission when compared with a contemporary simple cycle gas turbine. This reduction in power was translated into a smaller helicopter for the same payload and mission.(1)

Earlier estimates, using the Blackhawk helicopter, showed that the allowable specific weight of a CCE could be as high as 0.76 lb/hp and still be competitive with the gas turbine because of the large fuel saving. The computation was based on the allowable engine weight increase that would offset fuel and tankage weight saved, so that the take-off gross weight of the helicopter remained the same.(2)

The most fuel-efficient aircraft engine ever flown (1952) was the Napier Nomad (3000 + hp) compound cycle engine.(3) The Nomad's operating conditions were:

- o Shaft Horse Power -3000+
- o Diesel Core Speed -2050 rpm
- o Compressor Pressure Ratio -6.5:1
- o Diesel Inlet Air Temp -475F
- o Diesel Compression Ratio -8:1
- o Fuel Injection Pressure -15,000 psi
- o Max Firing Pressure - 2200 psi
- o Brake Mean Effective Pressure -205 psi
- o Equivalence Ratio -0.65
- o Diesel Exhaust Temp. -1250F
- o Specific Weight -1.0 lb/hp
- o BSFC -0.345 lb/hp-hr

During the 1950's all development effort was directed toward gas turbines, hence the Nomad never reached full scale production, but it represented the pinnacle of diesel aircraft engine technology. Applying today's technologies and designs to the Nomad could result in an engine having a specific weight under 0.60 lb/hp.

Based upon preliminary studies and the significant advancements in technology demonstrated under the GTEC/Air Force CCTE program[4,5]; the Army undertook a detailed engine analysis for a light helicopter application to establish CCE parameters that would best meet overall program objectives of fuel savings and system payoffs.

This executive summary presents the thermodynamic cycle analysis, component arrangement, weight, and configuration layout. CCE payoffs are compared with a contemporary gas turbine* for a typical 2-hr (+ 30 minute reserve) mission. In addition, major technology development areas are identified and discussed.

SUMMARY

Variants of 2-stroke and 4-stroke turbocharged and turbocompound engines were investigated. A 1 1/2 spool, 2-stroke, uniflow-scavenged CCE with aftercooling** was selected on the basis of specific fuel consumption (SFC-lbs/hp-hr) and engine weight.

When compared with the contemporary gas turbine for the 2 hour mission, the CCE offers these payoffs:

- o 31 percent less fuel consumption
- o 16 percent less engine and fuel weight
- o 8 percent less engine and fuel volume

These values are a result of tradeoff analyses which showed that large improvements in engine weight would more than compensate for a slight increase in fuel consumption. The fallouts translate into the following mission improvements:

- o 36 percent more payload or
- o 42 percent more range or
- o One-third more missions for the same fuel

A recent mission study by AVSCOM showed similar results.[6]

Three major technical development areas are identified and discussed. These are:

- o Piston ring/liner interface wear life
- o Exhaust valve life
- o Fuel injection with high heat release combustion

There are no technology barriers envisioned at this time which should preclude successful development of a CCE. However,

*Contemporary gas turbine is an advanced design (T-800 class) that employs demonstrated state-of-the-art component technologies scheduled for production in the early 1990's.

**1 1/2 spool - Turbine driven compressor with a bottoming turbine

2-stroke - One power stroke per crankshaft revolution

Uniflow - Flow from inlet to exhaust in one direction

Aftercooler - Heat exchanger between compressor and diesel cylinder

an agressive component technology effort is required to achieve the potential payoffs.

HELICOPTER ENGINE CONFIGURATION STUDY RESULTS

Nine different diesel-turbine combinations, as shown in Figure 2, were investigated during the initial screening phase of the study. The factors considered in making the selection were:

- o Specific fuel consumption
- o Engine weight
- o Expected aircraft mission

The objective was to identify the combination that would provide a maximum saving in mission fuel with the lightest weight engine, so as to achieve a maximum gain in range-payload for the vehicle. Turbocharged diesels (numbers 1, 2, and 3 on Figure 2) were eliminated early, simply because their fuel consumption and their weights were not competitive. Another general conclusion is that 4-stroke diesels 4 and 7 will be much heavier than their 2-stroke counterparts 6 and 9, but their fuel efficiency, although best, was not significantly better than a 2-stroke design. A third conclusion is that a 2-stroke, uniflow-scavenged design, 6 and 9, is much more efficient and lighter than a loop-scavenged design, 5 and 8. Therefore, the two arrangements numbered 6 and 9 were carried into the next step of the studies.

In the final analysis, the choice between 6 and 9 was based on considerations other than operation at full design power. The added turbine stage in No. 9 provided the needed flexibility to avoid variable geometry in the turbomachinery or variable ratio gearing to match the speeds of the diesel and turbine modules. Therefore, this arrangement, termed

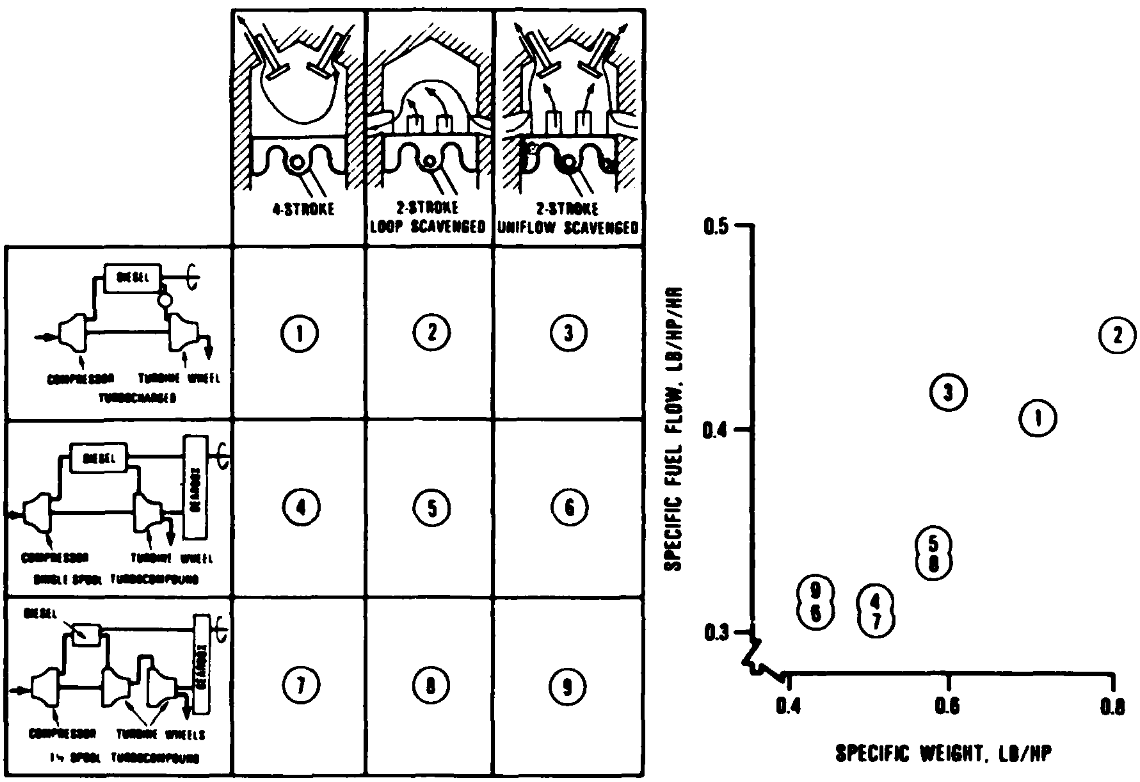


Figure 2. Nine Configurations Design Point (1000 HP) Diesel/Turbine Thermodynamic (SFC) and Weight Analysis.

a 1 1/2 spool module, offered a better gain in fuel consumption in the 50 percent power range where most of the mission is flown. The mission-power profile used to estimate the magnitude of the gains is shown in Figure 3.

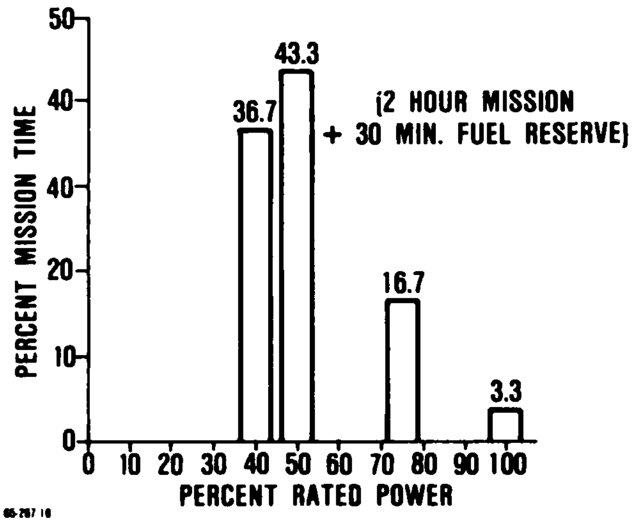


Figure 3. Mission Power/Time Profile.

The resulting comparison of specific fuel consumption as a function of shaft power for arrangements 6 and 9 is shown in Figure 4.

Installed engine weights, as reflected in Figure 2, include:

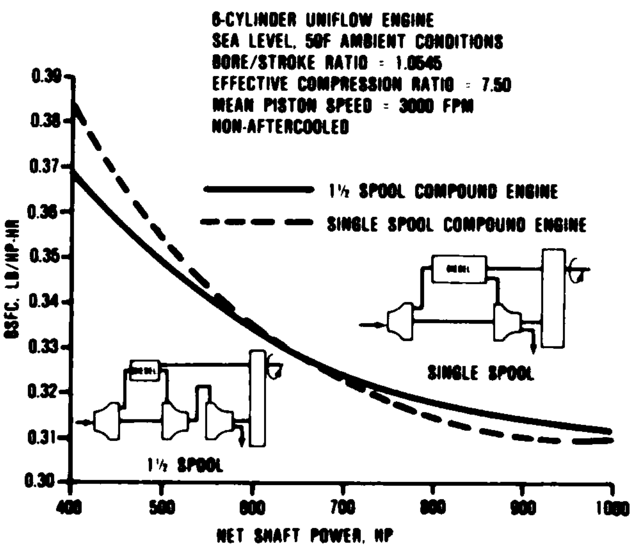
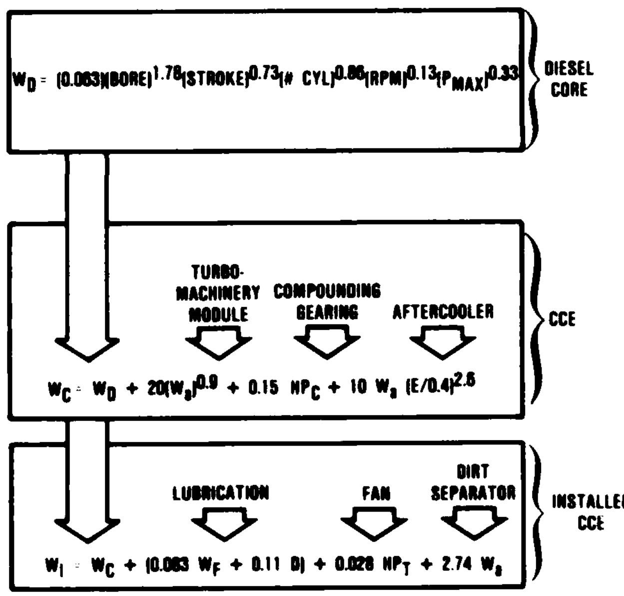


Figure 4. Specific Fuel Consumption as a Function of Power.

- o Diesel core
- o Basic CCE engine
- o Installation items

Previous methods for estimating internal combustion engine core weights were considered inadequate for this study. To develop an approach, five key engine design parameters (bore, stroke, number of cylinders, speed, and maximum firing pressure) were identified and their sensitivities quantified. Sensitivities were derived by least squares regression analysis of data from 21 different turbocharged or supercharged reciprocating aircraft engines. All weight estimates for the remaining items were based on data available from NASA and GTEC.

The resulting weight equation is shown in Figure 5.



W_D = DIESEL CORE PLUS ACCESSORIES WEIGHT — LB
W_C = UNINSTALLED COMPOUND ENGINE WEIGHT — LB
W_I = INSTALLED COMPOUND ENGINE WEIGHT — LB
P_{MAX} = MAXIMUM CYLINDER PRESSURE — PSIA
W_a = AIRFLOW — LB/SEC
W_f = FUEL FLOW — LB/HR
E = AFTERCOOLER EFFECTIVENESS
D = DIESEL DISPLACEMENT — CUBIC INCHES
HP_C = COMPOUND TURBINE HORSEPOWER
HP_T = TOTAL OUTPUT HORSEPOWER

Figure 5. Engine Weight Functions.

SELECTED ENGINE CONFIGURATION

Parametric design point and off-design trade-offs were conducted to evaluate the effects of cycle variants, such as, cylinder compression ratio, compressor pressure ratio, aftercooler effectiveness, and pressure drop across the cylinder. These trade-offs resulted in a 1 1/2 spool, aftercooled, two stroke uniflow scavenged CCE, with a thermodynamic cycle as shown in Figure 6.

An aftercooler was introduced to reduce cylinder inlet air temperature, so as to reduce combustion, ring-reversal and exhaust valve temperatures. Addition of the aftercooler and its weight was offset by reduced cylinder size and a lighter diesel core because of higher charge air density. More importantly, it will enhance engine life. However, a small SFC increase (0.02 lb/hp-hr) will be incurred.

The best SFC and engine weight balance was found to exist at high compressor pressure ratios (over 10). The diesel core effective compression ratio was limited to 7.5 in order to keep peak firing pressure below 3400 psia. A diesel flow pressure drop of 10 percent across the cylinder achieved the best compromise between overall cycle efficiency and weight.

Core design parameters are shown in Table 1. The rpm and P_{max} levels established were reduced from those demonstrated during the CCTE program, primarily to enhance life. The design point equivalence ratio* of 0.68 was selected because it is recognized as an

Table 1. Diesel Core Description.

o	**Engine RPM**	**6122**
o	**Airflow Rate, lb/sec**	**2.44**
o	**Bore, in.**	**3.10**
o	**Stroke, in.**	**2.94**
o	**No. of Cylinders**	**6**
o	**Displacement, in.^{3}**	**133.2**
o	**Equivalence Ratio**	**0.68**
o	**Peak Firing Pressure, P_{max} psia**	**3362**
o	**Effective Compression Ratio**	**7.5**
o	**BMEP, psi**	**393**

$$*\text{Equivalence Ratio} = \frac{\text{Actual Fuel/Air Ratio}}{\text{Stoich Fuel/Air Ratio}}$$

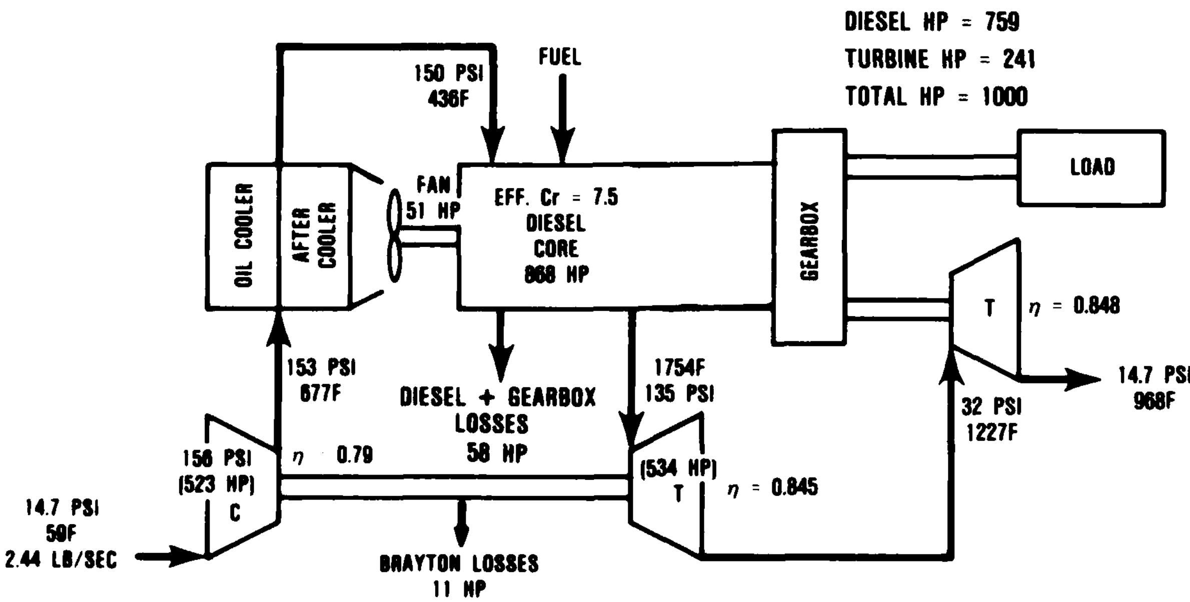


Figure 6. Sea Level, Standard Day, Design Point Operating Conditions of Selected 1/1/2 Spool Compound Cycle Engine.

industry-accepted value for nonvisible smoke. A six cylinder configuration was chosen for simplicity.

A conceptual design layout of the selected CCE is shown in Figure 7. The figure shows two major modules, i.e., turbomachinery and diesel core. The turbomachinery module is similar to the more familiar turboshaft engine. It has a typical gas generator spool with a two stage backward curved, broad range, high pressure ratio centrifugal compressor, driven by a single-stage, radial-inflow turbine. The half-spool axial power turbine is geared into the compounding gearbox. The turbomachinery is mounted into the V-form of the diesel core so as to minimize overall box volumes to less than 14 cubic feet, including oil cooler and aftercooler. The two-stroke diesel module has six cylinders, is uniflow scavenged, and has four exhaust valves per cylinder, which are activiated with overhead cams. Fuel injectors are located centrally in the cylinder heads. A low heat loss combustion chamber with thermally isolated and preferentially cooled cylinder liner/head and piston dome are used. The engine is oil cooled and fully self contained with all engine required-to-run controls and accessories. Total installed weight including oil, oil cooler, fan, and inlet air particle separator is 432 lbs for a specific weight of 0.43 lb/hp.

MISSION COMPARISON WITH GAS TURBINES

The CCE configuration selected for this study resulted from an analysis of many engine design and performance parameters to minimize the sum of engine plus fuel weight for the mission. This engine meets the major study objectives of at least a 30 percent savings in fuel.

The mission used in preliminary design is the Army's standard of 2 hours plus 30 minutes fuel reserve and is typical for a twin-engine light helicopter. The mission is flown at 4000 feet on a 95F day, and the engine is designed to be flat-rated at 1000 shp to the hot day/altitude conditions. For comparison, the simple cycle gas turbine was sized for 1400 shp at sea level standard day so that it could produce the same 1000 horsepower at 4000 feet, 95F.

Flat rating of the CCE on the other hand, is accomplished by increasing the turbocompressor spool speed 4.0 percent and increasing the trapped equivalence ratio from 0.68 to 0.80 for the short duration, rated power conditions.

The results of the mission comparison study are shown in Table 2. Total fuel, tank, and engine weights have been calculated under static operating conditions for a twin engine application. These results show a potential for:

- o 31.4 percent savings in fuel consumption
- o 15.8 percent savings in engine plus fuel weight
- o 8.5 percent savings in engine plus fuel volume
- o One-third more missions for a given quantity of fuel

These savings may also be translated into more range or more payload for the same gross weight vehicles:

- o 36.5 percent increase in payload or
- o 40.7 percent increase in range

ALTITUDE PERFORMANCE

Shaft horsepower and SFC as a function of altitude, for the selected CCE, are shown in Figure 8 for hot, standard and cold day conditions. Flat rating at 1000 shp for the various conditions is achieved by allowing the equivalence ratio to increase to a value of 0.80. This condition is reached at 4,000, 7,000, and 9,600 feet for hot, standard and cold days, respectively. The cold day SFC curve below 9,600 feet is affected by changes in fuel injection timing and trapped air equivalence ratio. On a standard day, engine operation at $\theta = 0.68$ is about equal to the hot day performance at $\Theta = 0.80$.

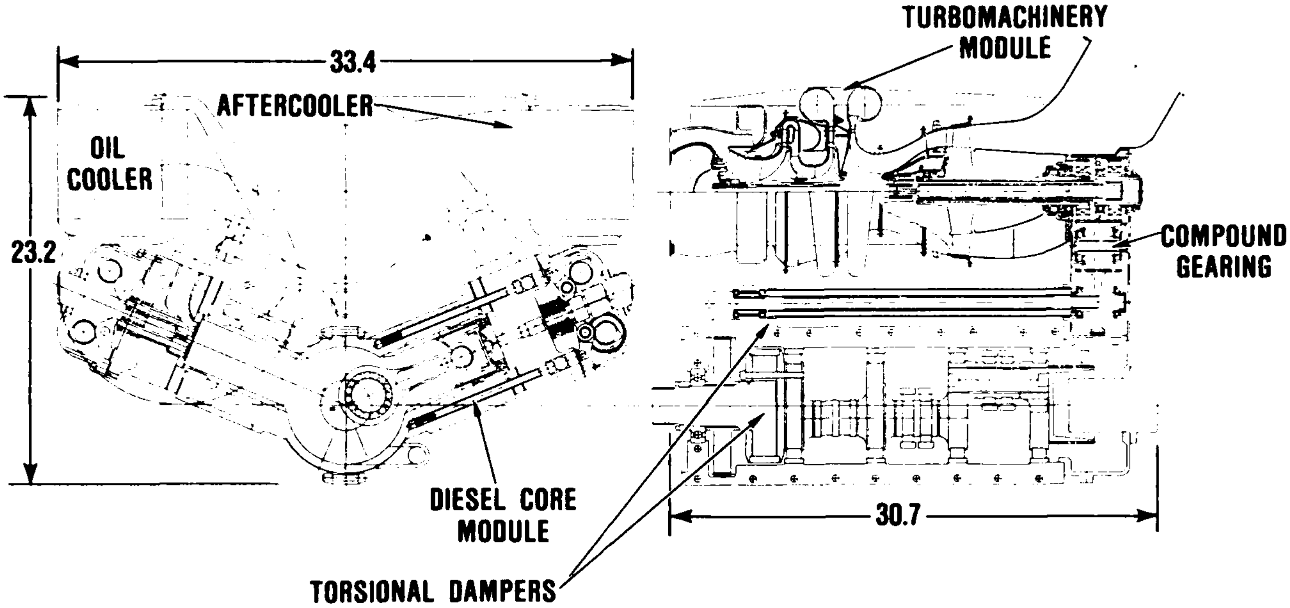


Figure 7. Conceptual Design of 1 1/2 Spool Compound Cycle Engine.

Table 2. CCE/Gas Turbine Consumption and Weight Comparison At 4000 Feet 95F Day.

Percent Power		Time (hours)	CCE BSFC (lb/hp-hr)	CCE Fuel (lbs)	Contemporary Gas Turbine BSFC (lb/hp-hr)	Contemporary Gas Turbine Fuel (lbs)
100		0.08	0.342	28.6	0.457	38.1
75		0.42	0.349	109.2	0.490	153.3
50		0.58	0.377	110.0	0.553	161.5
40		0.92	0.400	146.7	0.603	221.4
50	(reserve)	0.50	0.377	94.3	0.553	138.5
Totals		2.50		**488.7		712.8

	CCE	Contemporary Gas Turbine
Fuel	488.7	712.8
Fuel Tank Weight	83.0	121.1
Installed Engine Weight	432.4	358.0
Total: Fuel, Tank, and Engine	*1004.1	1191.9
For Two Engines	2008.3	2383.9

$$\text{*Percent Weight Savings: } 1.0 - \frac{\text{CCE Total Weight}}{\text{Gas Turbine Weight}} = 15.8$$

$$\text{**Percent Fuel Savings: } 1.0 - \frac{\text{CCE Total Fuel**}}{\text{Gas Turbine Fuel}} = 31.4$$

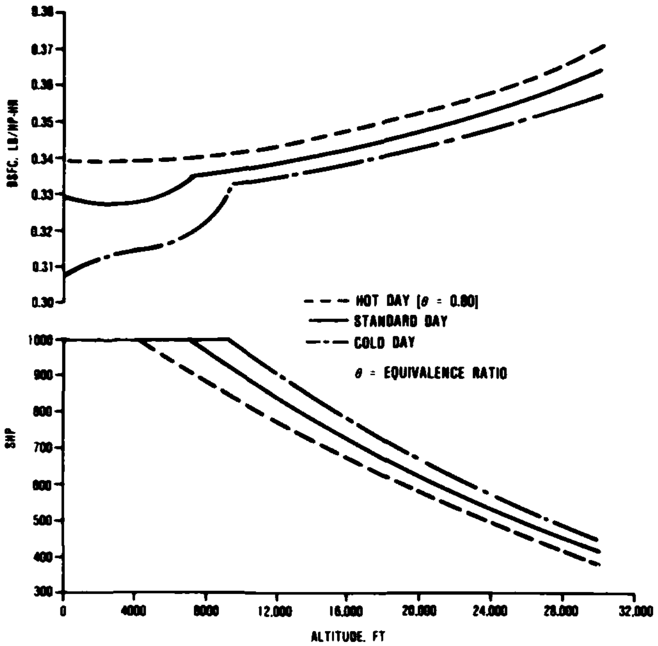


Figure 8. SHP and BSFC Performance of CCE Versus Altitude.

MAJOR TECHNOLOGY DEVELOPMENT AREAS

The turbomachinery module consists of state-of-the-art technology components. The diesel core configuration follows somewhat conventional design practices for two-stroke engines, but the cycle pressure, temperatures and speeds are somewhat higher and therefore beyond today's demonstrated diesel engine technologies.

Three major technology development areas have been indentified for the diesel core. They are in order of considered importance:

- o Piston ring/liner interface wear life
- o Exhaust valve life
- o Fuel injection with high heat release combustion

Piston Ring/Liner Interface Wear Life

Because a main objective is long engine life, the number one development challenge or life limiting factor of most concern is the wear rate of the piston ring/liner interface materials. Factors which influence wear are:

- o Piston velocity and engine speed
- o Piston ring/liner geometries
- o Surface topography
- o Material chemistry and properties
- o Oil film type and thickness
- o Operating pressures and temperatures
- o Contamination - foreign and self generated
- o Lubricant type and additives
- o Time between oil changes

Complex interactions between the different factors make it difficult to quantify overall effects on engine life. The qualitative effects are, however, well understood. A great deal of experience is available on low power density diesel engines but it is quite limited in its extension into the design regions of the CCE discussed here. Total system (single cylinder) testing under controlled environment conditions using best lubricant formulations and tribological couples is necessary to establish a technology baseline for CCE wear-life predictions.

Exhaust Valve Life

The exhaust valve life is the second most important item for CCE development. Exhaust gas valve temperature at full power on a hot day is several hundred degrees hotter than current engines. High temperature creep and fatigue resistant materials that also have high oxidation corrosion resistance will be required. Means to thermally isolate, insulate, and preferentially cool the valves and seats will be required.

Fuel Injection/Combustion

Fuel injection with high heat release combustion is considered to be the third area for development. The primary requirement for the fuel injection equipment for a direct-injected diesel is to distribute a uniform, finely atomized charge of fuel throughout the combustion chamber, at the right time and in the right quantity. If not, excessive peak

cylinder pressure could occur, exhaust smoke would increase, and engine life could be shortened. High speed requires high injection pressures for increased heat release rate combustion. A high pressure (>20,000 psi) electronically controlled hydromechanical type fuel injection system is considered the prime candidate.

MISSION PAYOFF SENSITIVITY

Figure 9 shows the percent improvements over a contemporary gas turbine in engine SFC (mission fuel weight), and range or payload as a funcion of diesel core speed. As diesel core rpm is increased, the required technology levels in the three major development areas are also increased for the improved performance.

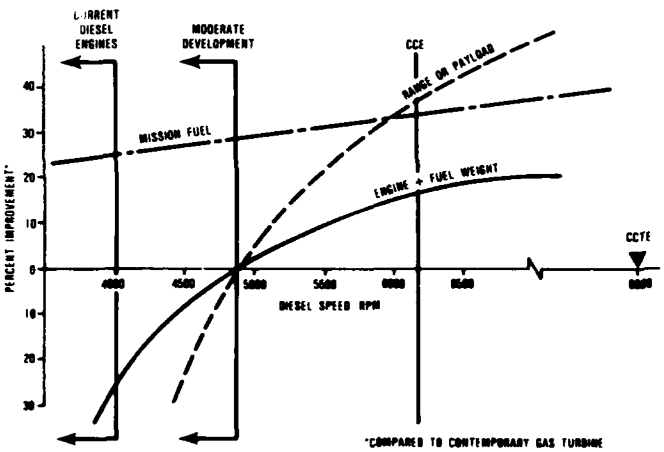


Figure 9. Potential Improvements as a Function of Diesel Engine Speed.

An engine based upon application of current technologies could provide a 20 percent saving in mission fuel; however, its weight would be unacceptable. Near-term (moderate) development could produce 25 percent fuel savings at an acceptable engine weight, but with no gain in range or payload. With an agressive concentrated thrust, however, the selected CCE offers a 31.4 percent saving in fuel and about a 40 percent improvement in range or payload for the same vehicle gross weight. It should be noted, again, that the CCTE engine was run at 8000 rpm under the AF/DARPA program and that the targeted speed for the CCE is well under that value.

CONCLUSION

Based on the standard two-hour design mission for helicopters, the compound cycle engine offers significant payoffs when compared with a comtemporary gas turbine:

- o 31 percent less fuel consumption
- o 36 percent more payload (or 42 percent more range)
- o One-third more missions per unit fuel

For longer missions, the CCE payoffs increase, consistent with the saving in fuel consumption.

RECOMMENDATIONS

Because the payoffs are so significant, it is recommended that the following activities be pursued vigorously:

- o <u>Piston Ring/Liner Interface Wear Life</u>

Expand lubricant formulation, advance tribology and uniflow scavenged single cylinder R&D activities currently underway on the ADEPT program.

- o <u>Exhaust Valve Life</u>

Demonstrate high power density, uniflow scavenged performance and evaluate alternate valving schemes.

- o <u>Fuel Injection/Combustion</u>

Expand the fuel injector/combustion effort started under CCTE on electronically-controlled, hydromechanical injectors.

- o <u>Overall CCE</u>

To demonstrate the overall viability of the diesel core, tests should be performed on a multi-cylinder engine/rig to confirm integration of technologies, core performance, and life and weight prediction methodologies.

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